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MEASUREMENTS OF PERFORMANCE OF PHOTOVOLTAIC
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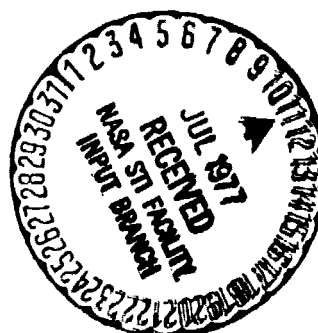
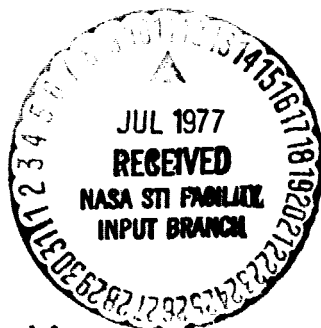
INDOOR AND OUTDOOR MEASUREMENTS OF PERFORMANCE OF PHOTOVOLTAIC ARRAYS

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ABSTRACT

A description of the techniques and methodology for making outdoor I-V measurements of solar cells is given. Temperature and irradiance measurement, experimental arrangement, data acquisition system and I-V data transformations are discussed. Data are presented comparing outdoor measurement to indoor measurements using a pulsed solar simulator.

INTRODUCTION

Performance measurement of solar cells, modules and arrays is a necessary adjunct to low-cost solar cell array development. Module performance data are needed for sub-array and array sizing. There is a need to match modules in sub-arrays to operating current and voltage. Data on finished arrays are also needed to determine baseline performance for eventual degradation analysis.

Generally, modules and arrays are too large to test using conventional steady-state solar simulators, hence other methods for obtaining performance (I-V) measurements must be used. The approach used by NASA-Lewis is to measure modules indoors using a long-arc xenon-lamp pulsed solar simulator, and outdoors using natural sunlight. The indoor pulsed simulator method has the advantages of easy availability and, because of the short duration of the irradiance pulse (2 msec), there is no heating of the solar cell arrays. Flash intensity is controlled and data are taken at room temperature. Only

minor data corrections are used to reach standard conditions of 28°C and 100 mW/cm^2 . However, to fully characterize module or array performance, data should also be obtained at actual operating conditions. These data are needed to assess the effects of temperature on the array performance. These effects would most probably appear only under steady-state illumination. To determine these effects, data need to be taken at a variety of irradiance and temperature levels. Current and voltage corrections, used to transform data to the standard 28°C , 100 mW/cm^2 conditions, can be large and may be significant sources of error. The purpose of this paper is to describe the techniques for obtaining and correcting module and array outdoor I-V measurements used at NASA-Lewis. The test arrangement and data transformations are discussed; also data comparing outdoor sunlight and indoor flash simulator measurements are presented.

EXPERIMENTAL APPROACH

Measurements Methodology

Figure 1 is a schematic drawing of the outdoor I-V measurement arrangement. The measurement procedures used are described in the Interim Solar Cell Testing Procedures for Terrestrial Applications (ref. 1). The module or array is oriented perpendicular to the sun. A reference cell whose spectral response is matched to the array under test is co-planar with the array. The reference cell mount has provisions for temperature control to maintain the temperature near 28°C . A 0.1Ω precision resistor is placed across the reference cell and the resulting voltage drop yields cell short

circuit current which is directly proportional to the irradiance.

Module temperature is obtained from a thermocouple taped to the rear of the test module directly behind a central cell. The thermocouple reference junction is maintained at 25° C and is located close to the module. This eliminates the need for long thermocouple extension leads. The relationship between actual cell temperature and means of thermocouple attachment will be described later.

To minimize voltage drop (IR) losses in the measurement apparatus, a conventional four-wire hookup (2 current leads, 2 voltage leads) is used. For individual modules, the four-wire attachment is made at the module binding posts or at the end of the integral cable. For arrays, the attachment is made at a junction box. Therefore, any small IR drop in these leads and in the inter-array wiring is included in the I-V measurement. An appropriate cable is used to bring the four I-V leads, the two thermocouple leads and the two reference cell leads indoors to a data acquisition system.

A programmable calculator is the central part of the automatic data system. The system includes the necessary voltmeters, a variable programmable power supply, a current measuring shunt and output devices. In about 30 seconds, approximately 50 data points in the power quadrant and several points beyond both open circuit voltage and short circuit current are obtained. Obtaining data outside the power quadrant assures full I-V curves after temperature and irradiance transformations.

Module Temperature Measurement

Cell temperature in the module or array is measured by a small bead thermocouple taped to the back of the module, directly behind a central

cell. The thermocouple is not directly attached to a cell because such attachment would destroy the integrity of the module. In order to determine the difference between temperatures measured in this way with actual cell temperature, comparisons were made on fully instrumentated modules. Holes were drilled through the module substrate and thermocouples were directly attached to the back surfaces of 10 of the 18 cells. In addition, two thermocouples were taped to the back of the module behind two cells. Figure 2 shows a temperature distribution of the 10 cells with thermocouples. The temperature of the indicated central cell is 50°C and the data numbers are temperature differences between each cell and the central cell. Temperatures of cells in the module ranged from 44°C to 51°C , while the thermocouple taped behind the indicated central cell read 47°C . The range of cell temperatures (7°C) was larger than the temperature difference between the indicated central cell and the module back (3°C) behind this same central cell. The second thermocouple taped to the module back was behind a corner cell (lower right in fig. 2). The difference between corner cell and module back was also 3°C . However, because this corner cell had a lower-than-average temperature, the taped thermocouple being 3°C cooler gave a very poor representation of the average temperature of cells in the module. Hence, the thermocouple taped behind a central cell was used to give indication of the average temperature of the module.

These data were repeated under a variety of ambient temperature conditions and incident irradiance levels. The trend of results remained the same. The taped thermocouple on the middle of the module back consistently gave a representative cell temperature.

It should be noted also that the reproducible spread of cell temperatures within the module represents an additional source of error. Since cell temperature is used in the I-V transformation equations, there is really no single temperature that can be used for all cells in the module or array. This leads to an uncertainty in the corrected I-V curves compared to data obtained under uniform conditions. However, under operating conditions, the modules will also reach this spread of cell temperatures, hence data taken under natural sunlight will be representative of actual module performance.

I-V Data Analysis

Voltage and current transformations. - During outdoor I-V measurements, data are taken at a wide variety of temperature and irradiance levels. Since the I-V data are generally used for comparison purposes or eventual degradation analysis, it is necessary to convert all data to standard conditions. These conditions have been defined to be 28° C and 100 mW/cm² as measured by a reference solar cell (ref. 1). Equations used for I-V curve transformation are found throughout the literature. The following equations are from Sandstrom (ref. 2):

$$\Delta I = I_{SC} \left(\frac{100}{E} - 1 \right) + \alpha (28 - T) A \quad (1)$$

$$I' = I + \Delta I \quad (2)$$

$$V' = V + \beta(28 - T) - \Delta I R_s - K(28 - T) I' \quad (3)$$

where

I, V, I_{SC} measured values of current, voltage and short-circuit current

$E \left(\frac{mW}{cm^2} \right)$ irradiance during measurement

$T(^{\circ}C)$ temperature during measurement

$A(cm^2)$ cell area

$I' V'$ current, voltage corrected to $28^{\circ} C$ and $100 mW/cm^2$

$\alpha \left(\frac{amps}{cm^2 \ ^{\circ}C} \right)$ current temperature coefficient

$\beta \left(\frac{volts}{^{\circ}C} \right)$ voltage temperature coefficient

R_S (ohms) series resistance

$K \left(\frac{ohms}{^{\circ}C} \right)$ curve correction coefficient

All the data and constants are assumed positive except β , the voltage temperature coefficient, which is negative.

The last two terms in the voltage transformation (Eq. (3)) are the series resistance term and the curve correction term. The series resistance term ($\Delta I R_S$) is proportional to the current transformation (ΔI) and is constant for all voltages. The curve correction term is negligible near open circuit voltage and has a small effect on short circuit current. The main effect of the curve correction term occurs near the maximum power point where it softens the I-V curve as temperature increases.

These last two terms are not normally used or needed for small temperature and irradiance corrections. For example, the pulsed simulator uses a computer program which incorporates only the irradiance and the α and β temperature corrections. However, for the range of corrections encountered in outdoor measurements, all correction terms are needed. For example, consider a 40 cm^2 terrestrial solar cell with a short circuit current of 1 ampere at 100 mW/cm^2 . If data are assumed to be taken at 80 mW/cm^2 and 38°C , a ΔI of about 190 mA will be obtained (200 mA for irradiance correction - 10 mA for the temperature correction). For a series resistance of $0.05 \Omega/\text{cell}$ a 9.5 mV/cell correction to the voltage transformation is obtained. This value represents about a 2% change in maximum power and clearly should be taken into account.

A value for the K coefficient is not readily available. If a K value of $1.25 \times 10^{-3} \text{ ohms}/^\circ\text{C}$ is assumed (ref. 2), with a current of 0.95A at maximum power, an additional voltage transformation of 11.9 mV/cell is obtained at the maximum power point. This also is about a 2 percent change and should be taken into account. However, the actual value of the K factor must be obtained from measurements of cells or modules at different temperatures. These data are not presently available, hence the K term correction is not presently being used.

Series resistance determination. - The method used at NASA-Lewis to determine the total series resistance of a module or array is based on the slope of the I-V curve near open circuit voltage. In this approach, the I-V data are adjusted for irradiance only. Next, the change in open

circuit voltage due to the irradiance correction transformation is noted ($\Delta V_{OC}(\text{meas})$). From simple theory for a cell with no series resistance we know:

$$I = I_o \left(e^{\frac{qV}{kT}} - 1 \right) - I_L \quad (4)$$

at open circuit voltage, $V = V_{OC}$, $I = 0$ and $I_L = I_{SC}$. Also $e(qV_{OC}/kT)$ is much larger than unity, hence we obtain:

$$I_{SC} = I_o \cdot \frac{qV_{OC}}{kT} \quad (5)$$

The ratio of short circuit currents for two irradiance levels becomes:

$$\frac{I_{SC1}}{I_{SC2}} = \frac{\left(I_o e^{\frac{qV_{OC1}}{kT}} \right)}{\left(I_o e^{\frac{qV_{OC2}}{kT}} \right)} \quad (6)$$

The I_o term cancels and taking natural logarithms of both sides leads to:

$$\ln \left(\frac{I_{SC1}}{I_{SC2}} \right) = \frac{q}{kT} \left(\Delta V_{OC} \right) \quad (7)$$

Since short-circuit current is proportional to irradiance ($I_{SC} = \text{constant} \times E$), we obtain:

$$\Delta V_{OC} = \frac{kT}{q} \ln \left(\frac{E_1}{E_2} \right) \quad (8)$$

where E_1 is 100 mW/cm² and E_2 is the irradiance at time of measurement.

The measured ΔV_{OC} will always be larger than the theoretical ΔV_{OC} due to series resistance. This increase is represented by

$$\Delta V_{OC(\text{meas})} - \Delta V_{OC(\text{theory})} = \Delta I_{SC} R_S \quad (9)$$

where ΔI_{SC} is the change in short-circuit current due to the irradiance transformation. This leads to a value of series resistance that can be used in the I-V transformation equations.

Flash Simulator - Outdoors Measurement Comparison

Several modules and arrays have been measured both outdoors and with the flash simulator indoors. This provides a basis of comparison of the two methods. The data were taken using the same reference cell indoors and outdoors. This greatly reduces possible errors due to spectral mismatch. Table I shows the results of measurements on four typical metal-backed modules. The outdoor measurements were taken at an irradiance of 78 mW/cm^2 as measured by the reference cell. Module temperature was 36° C as measured by the taped thermocouple. The flash simulator measurements were performed at room temperature and at an intensity within 2 percent of the 100 mW/cm^2 irradiance level. All data are corrected to 28° C and 100 mW/cm^2 .

An array of six series-connected fiberglass-backed modules was also measured inside and outdoors. These comparisons are presented in Table II. In this case, the outdoor data were measured at 97.7 mW/cm^2 at an array temperature of 41° C .

In both cases, there is excellent agreement in short-circuit current (outdoors about 0.5 percent higher); good agreement in open-circuit voltage

(outdoors about 1 percent lower); and only fair agreement in maximum power (outdoors nearly 3 percent lower. The difference in short circuit current is well within the measurement accuracies of the two systems. A difference of 1% in open circuit voltage corresponds to about a 3° C error in temperature measurement. This difference may be related to the spread in temperatures within the modules as described earlier. This magnitude of error is not great, however. The maximum power obtained outdoors is almost 3 percent lower than the flash simulator results. This difference is too large to be readily attributed to measurement errors. It is most likely caused by the lack of a K factor correction term. The data were taken at temperatures above 28° C and the K term corrects for a softening of the knee of the I-V curve at higher temperatures. Hence the correction would be in the proper direction. Its estimated magnitude of 2-3 percent would account for the difference observed.

SUMMARY

The techniques and methodology for making outdoor I-V measurements at NASA-Lewis have been described. Temperature measurements indicate a significant spread of individual cell temperatures within the same module when the module is outdoors in sunlight. In order to make proper I-V data transformations to a standard set of temperature and irradiance corrections, several module or array parameters must be known. Not only are the values of the current and voltage temperature coefficients (α and β) needed, but also values for module or array series resistance and K factor correction coefficient are necessary for most accurate measurements

REFERENCES

1. Brandhorst, Henry W., Jr., et al.: Interim Solar Cell Testing Procedures for Terrestrial Applications. NASA TM X-71771 (1975).
2. Sandstrom, J. P.: A Method for Predicting Solar Cell Current-Voltage Characteristics as a Function of Incident Solar Intensity and Cell Temperature. 6th Photovoltaic Specialists Conference, Vol. I, p. 199, March 1967.

TABLE I. - COMPARISON OF OUTDOOR TO FLASH I-V MEASUREMENTS
AVERAGE OF 4 SIMILAR MODULES

	<u>DATA TAKEN AT 78 MW/CM² 36° C</u>		
	<u>FLASH</u>	<u>OUTDOORS</u>	<u>% DIFF.</u>
I_{sc}	.526 A	.528	+ 0.4%
V_{oc}	14.0 V	13.8	- 1.2
P_{max}	5.78 W	5.62	- 2.8

**TABLE II. - COMPARISON OF OUTDOOR TO FLASH I-V MEASUREMENTS
ARRAY OF SIX FIBERGLASS BACKED MODULES**

	<u>FLASH</u>	<u>OUTDOORS</u>	<u>% DIFF.</u>
I_{sc}	1.467	1.478	0.7
V_{oc}	76.0	75.5	- 0.7
P_{max}	84.0	81.6	- 2.9

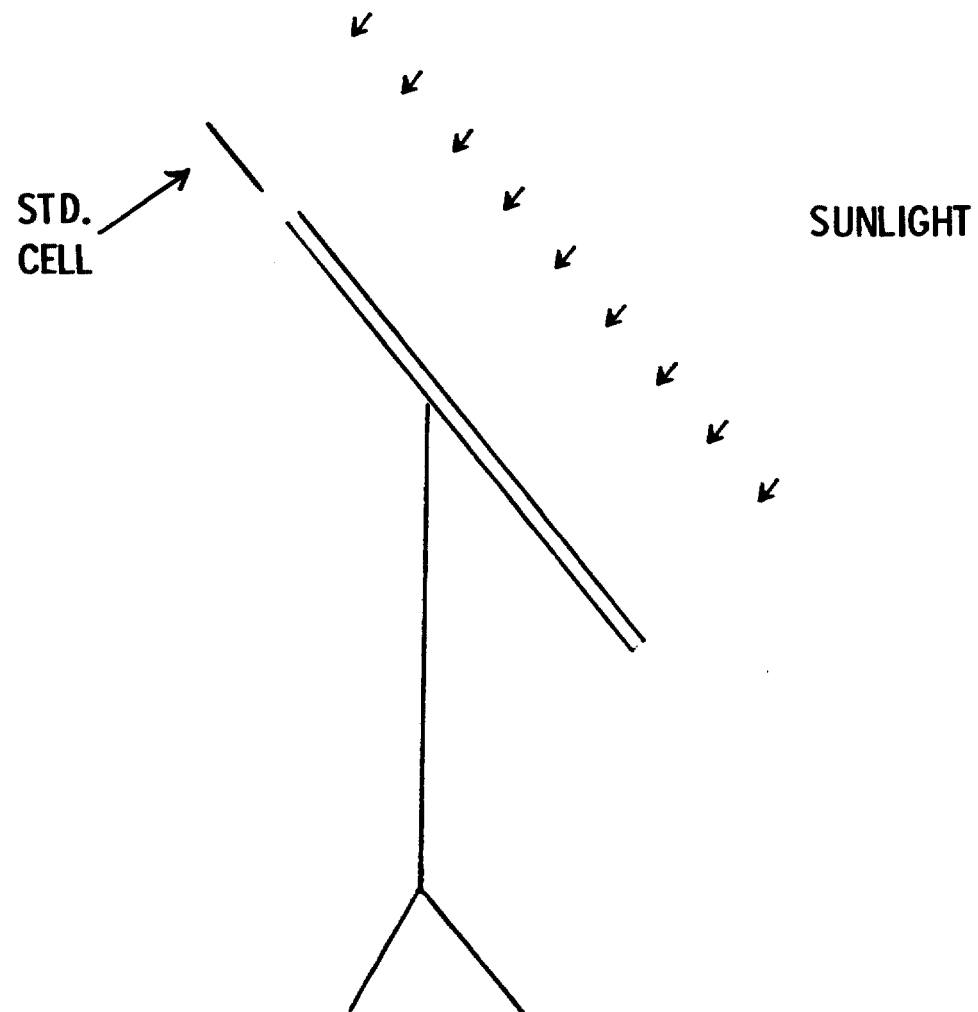


Figure 1. - Outdoor setup for module and array I-V measurements

X	X	X	X	X	X
-X			+X		-2
X	X	X	X	X	X
	0		-1		
X	X	X	X	X	X
-6		-4			-5

Figure 2. - Cell temperature distribution on 18 cell modules, temp. of indicated cell 50 C, temp. behind indicated cell 47 C